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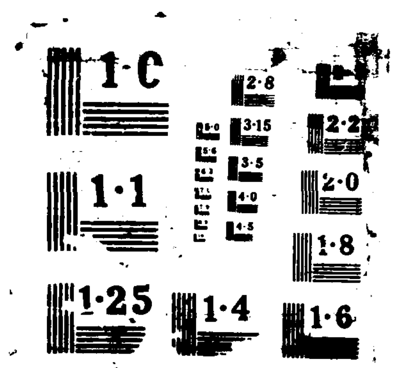
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Structures Technical Memorandum 464

A REVIEW OF MULTIAXIAL FATIGUE AND FRACTURE OF FIBRE-REINFORCED COMPOSITES (U)

by

P.W. BEAVER

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16. ABSTRACT
A review of the limited number of papers in the literature on multiaxial fatigue and fracture of fibre-reinforced composites has shown that biaxial stress states can have a significant effect on both the fatigue and fracture properties of these materials. In addition, none of the presently available failure theories for composites agrees with the observed experimental results with sufficient accuracy to be confidently used for design purposes.

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CONTENTS

NOTATION

σ_1, σ_2, σ_6	normal and shear stresses in the direction of principal material axes
X, Y, S,	tensile strengths in the principal material directions and the 0° - 90° principal shear strength
X', Y'	compressive strengths in the principal material directions
K_1, K_2	constants evaluated under combined stress tests
F_{12}	normal stress interaction component of a strength tensor
$\lambda = \sigma_1/\sigma_2$	biaxial stress ratio
X_0	yield strength for an unnotched uniaxial specimen
$\Delta\sigma$	axial tensile stress range
$\Delta\tau$	shear stress range
N_f	number of cycles to failure
da/dN	crack growth rate
ΔK	stress intensity factor range

1. INTRODUCTION

The use of fibre-reinforced composites in high performance structures and components, such as found in the aircraft and power generation industries, has increased rapidly in recent years. Their high specific strength and specific modulus, excellent corrosion properties and design flexibility make them ideally suited for many applications, especially when there is a need to save weight and conserve energy. However, the ability to predict the strength and safe fatigue life of composite structures and components has not kept pace with the increase in the number of new applications, i.e. design in composites has been hampered by the lack of proven design procedures.

Most design data for composite materials are obtained by testing laboratory specimens of simple geometry with the principal fibre direction usually parallel to the loading direction. In addition the specimens are treated as if they were homogeneous and that the failure condition is defined by separation into two pieces. In comparison, most engineering structures and components operate under multiaxial loading conditions and the general stress states may be further complicated by the presence of geometric discontinuities, such as notches, holes or joints. Furthermore, it is difficult to fabricate a homogeneous and defect-free composite component. Such components can fail in several different modes prior to complete separation.

At present, the amount of multiaxial fatigue and fracture research on engineering materials has been limited compared with that undertaken for uniaxial loading conditions. This situation has arisen for the following reasons:

i) There has been a lack of reliable multiaxial or biaxial testing machines as the design, development and experimental work associated with building such equipment tends to be complicated, time consuming and expensive compared with that for uniaxial testing systems [1,2].

ii) Intricate specimen designs are required, hence the specimens also are expensive [3].

iii) There is no substantial theoretical framework for analysing the data [4].

iv) The experimental work is time consuming.

v) A large number of test results are required to develop and prove or disprove empirical criteria [3].

The influence of multiaxial stresses on material properties is starting to receive considerable attention [5] as some isotropic materials have shown significant biaxial loading effects. For example, a recent review of the literature [6, 7] has shown that for metals the more damaging biaxial stress states can (compared with uniaxial tension) decrease the low-cycle fatigue life by factors of up to 20, accelerate fatigue crack growth rates by factors of 3 to 4, and decrease critical stress intensity factors and stress intensity notch correction factors by up to 50%. The effects of multiaxial stressing on the fatigue and fracture properties of fibre-reinforced composites are recognized as being even more complex than for metals because (1) biaxial stresses may enhance the damage during loading as a result of the anistropy of strength and stiffness, and (2) several additional problems are encountered during multiaxial testing of composites, such as premature failure of a specimen near the end attachments as a result of poor load transfer.

The objective of this report is to review the limited literature on the effects of multiaxial stress on the fatigue and fracture properties of fibre-reinforced composites. To the best of the author's knowledge no such review has been published.

2. MULTIAXIAL TESTING TECHNIQUES

A wide variety of techniques has been used to test laboratory specimens under multiaxial stress states [8,9]. Of these only three appear useful for studying the complex behaviour of composite materials

under such stresses: these are the off-axis [10,11], the thin-walled tubular [11-14] and the cruciform [11, 15-17] specimen methods.

The off-axis (Fig. 1(a)) method is the simplest, cheapest and most widely used method of measuring the biaxial stress-strain behaviour relative to the fibre direction. However, this method has several limitations, the most significant being (1) the lack of to independent control of the biaxial stress components, so that only a limited range of stress states is possible, and (2) that the application of the applied stress produces a shear in the material at the grips, which may cause premature failure in that region.

A greater range of biaxial stress states can be achieved by subjecting thin-walled tubular specimens to a combination of axial loading, torsion and internal and/or external pressure, Fig. 1(b). This specimen geometry is more versatile than the off-axis geometry as it is possible to apply any desired biaxial stress state (with or without proportional loading) together with triaxial stress states, although these are seldom used. Tubular specimens are very useful for the yield and fracture testing of unnotched composites. However, several of the problems with this technique are:

i) It is difficult to fabricate high quality tubes with no overlaps or discontinuities in the reinforcement and yet with a uniform wall thickness.

ii) The specimens are expensive.

iii) Specialised testing equipment is required.

iv) The use of oil to pressurise tubes can lead to environmental effects on crack initiation and propagation. [This can be minimised by the use of a rubber sleeve to prevent contact between the oil and the specimen surface].

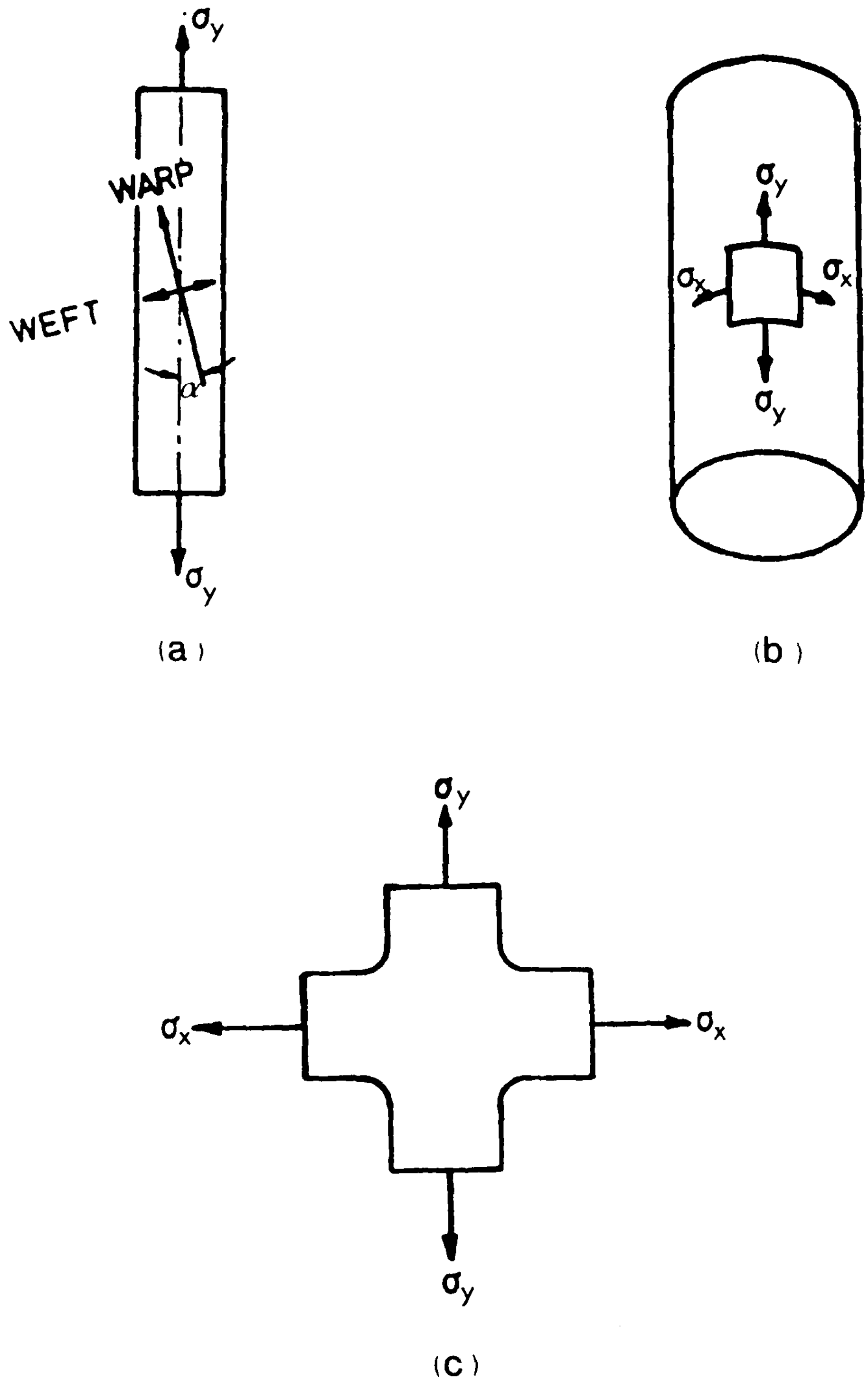


FIG. 1 Schematic representation of (a) the off-axis, (b) thin-walled tubular and (c) cruciform methods for producing biaxial stress states.

v) The hydrowedge effect may be encountered, that is, high pressure oil may enter a crack and wedge it open thereby providing an additional mode I opening stress. [This effect can also be minimised by using a rubber sleeve].

vi) It is difficult to design specimen end attachments to give good load transfers without failures in these regions.

vii) Fatigue crack propagation tests with through-thickness cracks are impossible.

A full range of biaxial stress states can also be achieved in flat cruciform-shaped specimens by simultaneously applying two principal stresses σ_1 and σ_2 along mutually perpendicular loading arms, Fig. 1(c). This technique is the most suitable means for biaxial testing of notched composites and for biaxial fatigue crack propagation studies, and has been used with some success for yield and fracture testing of a few composite materials. Compared with tubular specimens, this type of specimen is easier and cheaper to fabricate, fibre overlaps and discontinuities are avoided, and there are no environmental or hydrowedge effects from a pressurising fluid. However, biaxial testing of cruciform-shaped specimens still requires specialised testing equipment and the specimens are still expensive. Other disadvantages of this technique are:

a) Stress determinations and strain measurements in the test area are difficult.

b) Differences between the stiffnesses of the loading arms and the test area exist. These differences, which depend on stress state, make it difficult to test in equibiaxial tension.

c) Problems can be encountered in testing unnotched specimens, as premature failure may occur at areas of stress concentration such as corner fillets.

3. MULTIAXIAL FAILURE CRITERIA FOR BOTH STATIC AND CYCLIC LOADING

At present more than 40 multiaxial failure theories for composites have been proposed [18] which can be used for both static and cyclic loading. Most of these are based on only a limited amount of experimental data since multiaxial testing is both expensive and difficult. Moreover, these theories all use complete separation as the failure criterion and do not consider the various deformation mechanisms such as debonding, resin cracking, delamination or fibre fracture which can produce local failure before complete separation occurs. Owen and Rice [19] found that the mechanisms which cause a composite to fail depend on the matrix/fibre combination, specimen design, type of loading and stress state.

There are two main groups of failure theories for anistropic materials under biaxial loading conditions. Group 1 theories require only the normal stresses and shear stresses in the direction of the principal material axes whereas the theories in the second group require both biaxial strength values and shear strength values. Some of the better known failure theories in each group for composite materials under plane stress conditions are listed in Table 1. These failure theories are generally represented graphically as a surface in 3-dimensional Cartesian space using σ_1, σ_2 and σ_6 as the co-ordinate axes, where σ_1 and σ_2 are the in-plane normal stresses, and σ_6 is the in-plane shear stress in the directions of the principal material axes. In practice it is easier to represent a failure surface by a series of planar sections through the surface, examples of which are shown in Fig. 2 for glass-polyester composites.

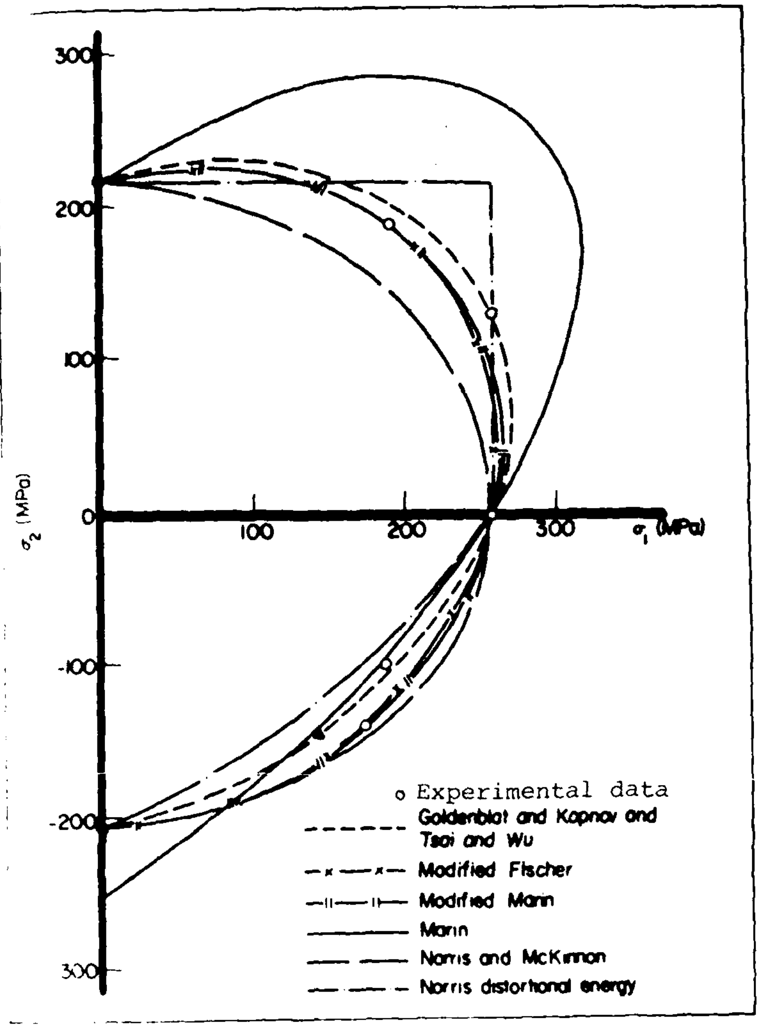
Thorough investigation of any failure theory requires a comparison of experimental data from biaxial tests over a wide range of values of σ_1, σ_2 and σ_6. Most of the failure theories have been supported by data obtained from static off-axis tests to rupture [10]. Unfortunately, it is difficult to discriminate between the various theories by these tests because they cover only a small part of the failure surface [10]. For better discrimination, Owen, Found, Rice and Griffith [10,11,12,14,18-

TABLE 1: Some of the better known static failure theories for anistropic materials under plane stress conditions [14].

1.	*Goldenblat and Kopnov*	$\frac{1}{2}\left(\frac{1}{X}-\frac{1}{X'}\right)\sigma_1+\frac{1}{2}\left(\frac{1}{Y}-\frac{1}{Y'}\right)\sigma_2+\left[\frac{1}{4}\left(\frac{1}{X}+\frac{1}{X'}\right)^2\sigma_1^2+\frac{1}{4}\left(\frac{1}{Y}+\frac{1}{Y'}\right)^2\sigma_2^2+2F_{12}\sigma_1\sigma_2+\frac{\sigma_6^2}{S}\right]^{1/2}=1$
2.	*Tsai and Wu*	$\left(\frac{1}{X}-\frac{1}{X'}\right)\sigma_1+\left(\frac{1}{Y}-\frac{1}{Y'}\right)\sigma_2+\frac{\sigma_1^2}{XX'}+\frac{\sigma_2^2}{YY'}+2F_{12}\sigma_1\sigma_2+\frac{\sigma_6^2}{S}=1$
3.	*Modified Fischer*	$\frac{\sigma_1^2}{X^2}-\frac{K_1\sigma_1\sigma_2}{XY}+\frac{\sigma_2^2}{Y}+\frac{\sigma_6^2}{S}=1$
4.	*Modified Marin*	$\frac{\sigma_1^2-K_2\sigma_1\sigma_2}{XX'}+\frac{\sigma_2^2}{YY'}+\left(\frac{X'-X}{XX'}\right)\sigma_1+\left(\frac{Y'-Y}{YY'}\right)\sigma_2+\frac{\sigma_6^2}{S}=1$
5.	*Marin*	$\left(\frac{X'-X}{XX'}\right)\sigma_1+\left(\frac{1}{Y}-\frac{Y}{XX'}\right)\sigma_2+\left(\frac{2}{XX'}-\frac{X'X-S(X'-X-X'\left[\frac{X}{Y}\right]+Y)}{XX'S^2}\right)\sigma_1\sigma_2+\frac{\sigma_1^2}{XX'}+\frac{\sigma_2^2}{XX'}=1$
6.	*Norris and McKinnon*	$\frac{\sigma_1^2}{X}+\frac{\sigma_2^2}{Y}+\frac{\sigma_6^2}{S}=1$
7.	*Norris distortional energy*	$\frac{\sigma_1^2}{X}-\frac{\sigma_1\sigma_2}{XY}+\frac{\sigma_2^2}{Y}+\frac{\sigma_6^2}{S}=1$

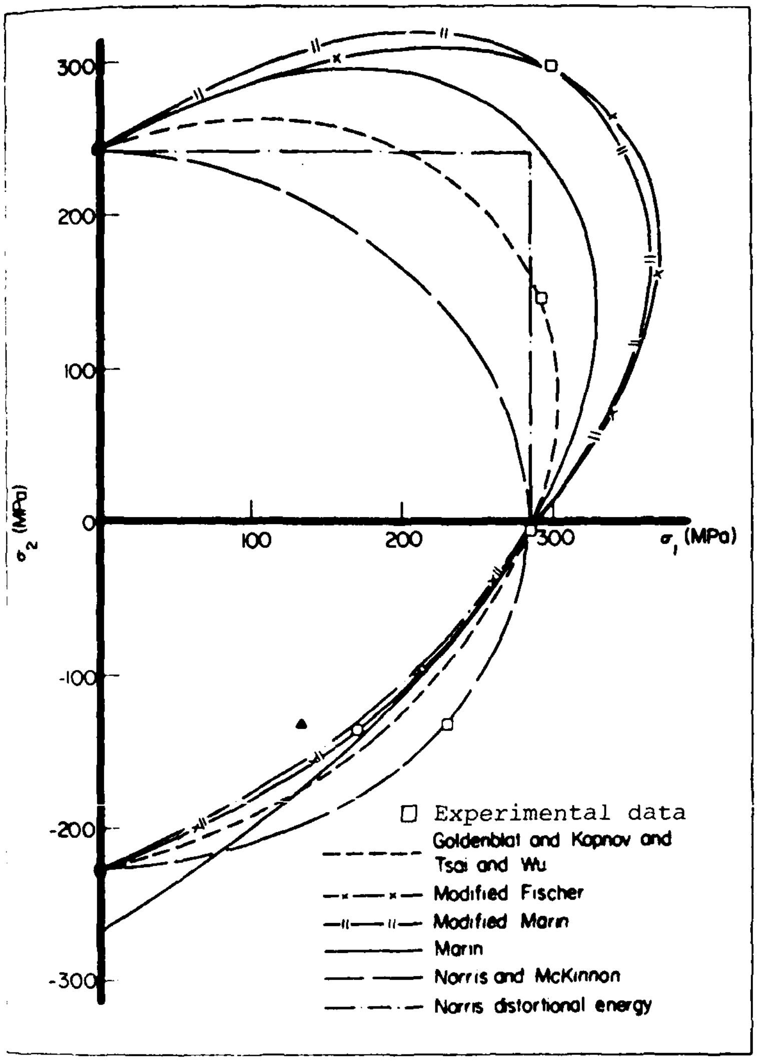
NOTATION

$\sigma_1, \sigma_2, \sigma_6$	normal and shear stresses in the direction of the principal material axes
X, Y, S	tensile strengths in the principal material directions and the 0°-90° principal shear strength
X', Y'	compressive strengths in the principal material directions
K_1, K_2	constants evaluated under combined stress tests
F_{12}	normal stress interaction component of a strength tensor



(a)

FIG. 2 Comparison of theoretical failure curves with experimental results for two glass-polyester composites (a) Y449/T500 and (b) Y449/T500P [14] (σ_1 and σ_2 are the stresses in the directions of the principal material axes).



300
200
100
0
-100
-200
-300
100
200
300
σ_2 (MPa)
σ_1 (MPa)
Experimental data
Goldenblat and Kopnov and Tsai and Wu
Modified Fischer
Modified Marin
Marin
Norris and McKinnon
Norris distortional energy

(b)

FIG. 2 (cont)

21] evaluated the various failure theories for several glass-polyester composites for both static and cyclic loading using thin-walled tubes under combined axial loading and internal/external pressure. This method offers the most comprehensive way of evaluating the complete failure surface. They tested over 1200 thin-walled tubular specimens under various biaxial loading conditions during a ten year period, and the main conclusions from their work are as follows:

i) None of the Group 1 theories was entirely adequate as a different failure theory is required for each stress octant.

ii) The fit of a failure theory varies from one material to another and is worse for fatigue loading than for static loading.

iii) A reasonable fit between the Group 2 theories and experimental results can only be achieved by a subjective choice of the biaxial data, because the shape of the failure surface is dependent on (a) the stress ratio chosen to evaluate the interaction coefficients F_{12} and K_2, and (b) the value of the in-plane shear strength σ_6 (determined from a torsion test) which is a function of the length of the tubular specimens used.

iv) The shapes of the Group 2 failure surfaces are also very sensitive to experimental scatter (which is significant and should be treated statistically) and to changing failure modes.

v) Existing failure theories do not take into account the various deformation mechanisms and failure modes which are dependent on lay-up, specimen design and stress state.

vi) For most commercial applications of fibre-reinforced composites the expense and effort in using thin-walled tubular specimens to evaluate the various failure theories cannot be justified.

The overall conclusion from this comprehensive research program was that any failure theory should be used with extreme caution. Similarly, Rowlands [22,23] concluded that none of the failure theories agreed with his experimental results with sufficient accuracy to be confidently used in design. Found [11] later suggested that a conservative estimate of failure for design purposes, for both biaxial static and fatigue loading conditions, could be obtained for tension/tension stress states by using the Norris interaction (Norris and McKinnon) theory [14] i.e.

$$\left(\frac{\sigma_1}{X}\right)^2 + \left(\frac{\sigma_2}{Y}\right)^2 = 1 \qquad (1)$$

and for tension/compression stress states by using the maximum shear stress theory i.e.

$$\frac{\sigma_1}{X} - \frac{\sigma_2}{Y'} = 1 \qquad (2)$$

However, he suggested that further work was needed to verify these simple criteria.

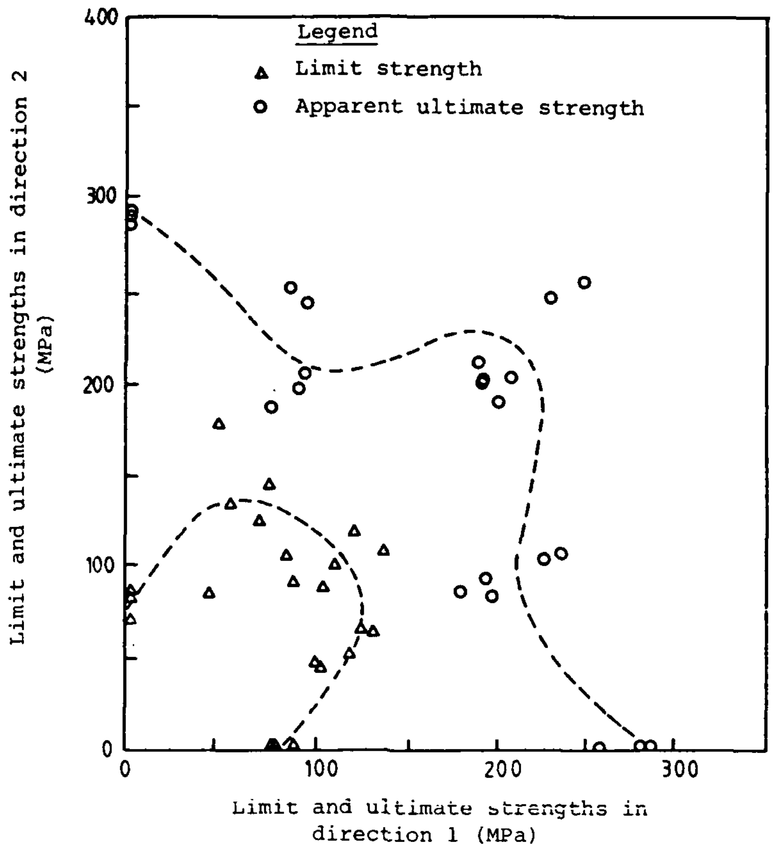
4. EFFECTS OF BIAXIAL LOADING ON STATIC STRENGTH

The effects of biaxial loading on the static strength of composite materials have been determined by only a few workers and for different specimen geometries. Bert, Mayberry and Ray [15] tested glass-epoxy (181-style E-glass cloth/Epon 828 E-epoxy) unnotched cruciform-shaped specimens in biaxial tension. They found that the values of the limit strength (0.01 percent strain offset) generally increased as the stress state changed from uniaxial tension to biaxial stress ratios of $\lambda = 0.5$, 1.0 and 2.0 as shown in Figs 3(a) and (b) [$\lambda = \sigma_2/\sigma_1$, where σ_1 and σ_2 are the maximum and minimum stresses in the directions of the principal material axes]. The ultimate strength values were also dependent on stress state. However these differences, when expressed as a percentage of the uniaxial value, were smaller than those for the limit strength values.

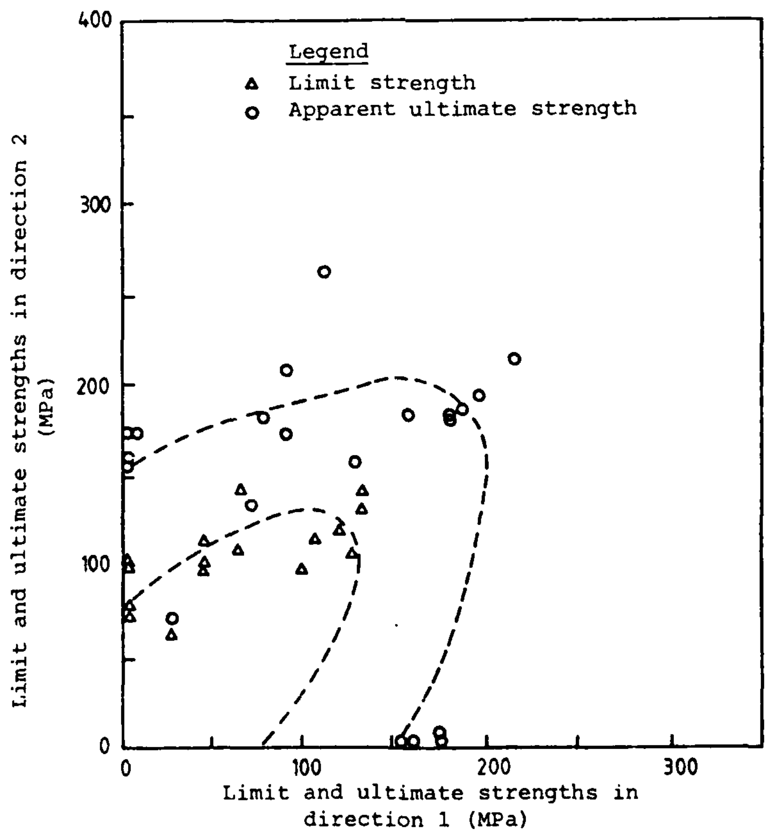
The effects of biaxial stress ratio on the static failure strengths of plain weave fabric, woven roving fabric and chopped strand mat glass-polyester composites were determined by Owen and coworkers [14,20,21] when evaluating the various failure theories described in the previous Section. They found that the maximum hoop stress at failure in the thin-walled tubular specimens (with the principal material axis parallel to the principal loading direction) increased as the biaxial stress ratio λ changed from -1.0 through to 0.5, and then decreased slightly for $\lambda = 1.0$ as shown for example in Fig. 4(a) and Table 2. The effects of biaxial loading on the failure strength were even more pronounced when the principal material axis was at 45° to the principal loading direction, Fig. 4(b) and Table 2. These results suggest that the layup of the composite is important in determining the magnitude of the biaxial load effect on the static strength of composites.

Guess and Gerstle [24] using unnotched, thin-walled, filament-wound tubular specimens also found that the static failure strengths of two graphite - and one Kevlar - epoxy composites were, in general, significantly greater for biaxial tension than for either axial or circumferential uniaxial tension, Table 3. They suggested that in the composite layups which they tested, the reinforcing effect of the fibres is greater with biaxial stress states. Similarly, Hotter, Schelling and Krauss [25] found that the failure strengths of unnotched thin-walled tubular specimens made from a glass-epoxy composite were greater in biaxial tension than uniaxial tension.

More recently, Jones, Poulose and Liebowitz [26] tested graphite-epoxy cruciform-shaped specimens containing central holes in biaxial tension. They found that the biaxial stress ratio λ had a significant effect on both the fracture plane and the static failure strength. For quasi-isotropic $[0/\pm45/90]_s$ laminates the static strength values increased by a factor of 1.44 as λ increased from 0 to 1, Table 4, and the fracture plane rotated from being one at 90° to the principal loading direction to one at approximately 45°. Daniel [27] also found that the static strengths of quasi-isotropic graphite-epoxy specimens of similar geometry



(a)



(b)

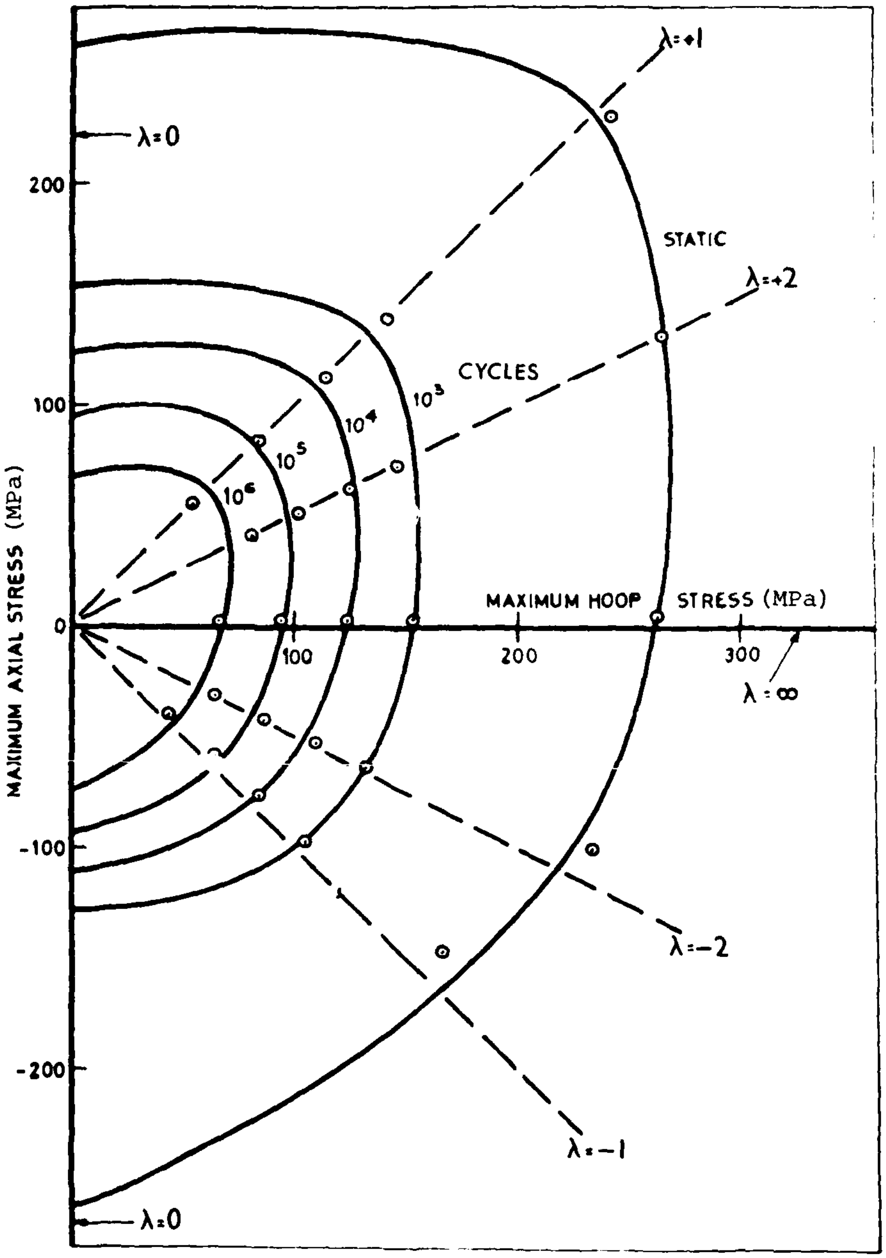
FIG. 3 Biaxial-tension strength envelopes for two different lay ups of a glass-epoxy composite (a) four parallel-ply lay up and (b) four-ply symmetrically cross lay up [15].

TABLE 2: Effects of biaxial stress ratio on the failure stresses of a glass fabric (TYGLASS Y449) - polyester resin (BEETLE L2615 BIP Chemicals Ltd) composite [21].

Orientation of fibres with respect to the principal loading direction (α)	Applied biaxial stress ratio ($\lambda = \sigma_{HOOP}/\sigma_{AXIAL}$)	Stress at failure (MPa)	
		σ_{HOOP}	σ_{RADIAL}
0°	$-\infty$ (axial compression)	0	-266
	- 1.0	167	-149
	- 0.5	237	-62
	0	266	0
	+0.5	266	132
	+1.0	242	233
	$+\infty$ (axial tension)	0	266
45°	$-\infty$ (axial compression)	0	-200
	- 1.0	103	-91
	-0.5	156	-64
	0	204	0
	+0.5	270	134
	+1.0	233	241
	$+\infty$ (axial tension)	0	200

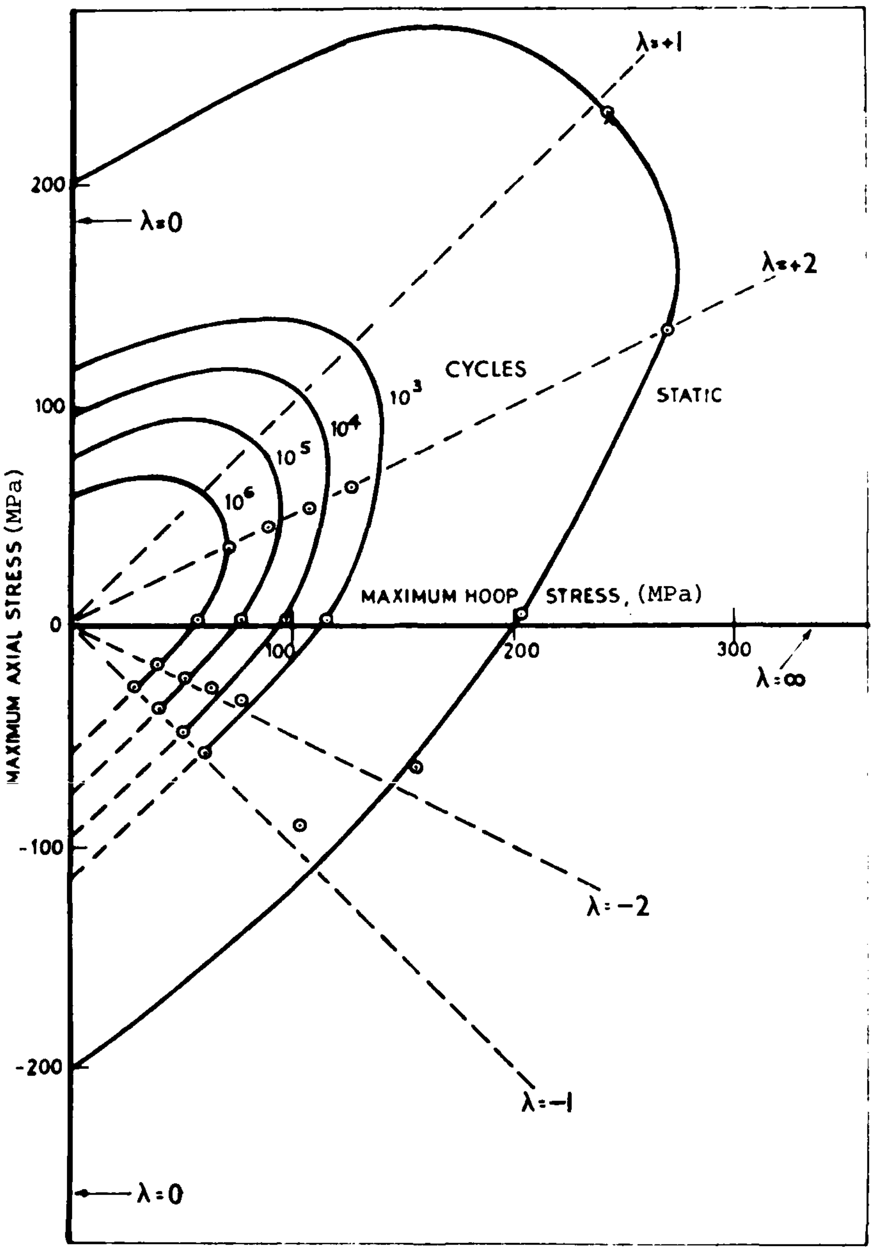
TABLE 3: The effect of biaxial stress ratio on the failure strength values (normalized with respect to the uniaxial values) for two graphite - and one Kevlar-epoxy composites [24] [Z and θ represent the axial and circumferential directions of tubular specimens respectively].

Filament/resin	Stress ratios $\sigma_\theta:\sigma_Z$	Normalized strengths $\frac{\sigma_\theta}{F_\theta}$	$\frac{\sigma_Z}{F_Z}$
T75/332 - T403	0:1	0.0	1.10
	1:0	1.02	0.00
	1:0	0.98	0.00
	1:1	1.071	1.10
T400/332-T403	1:0	1.064	0.00
	1:0	1.013	0.00
	1:0	0.922	0.00
	1:1	1.146	1.18
	2:1	1.429	0.74
Kevlar 49/332-T403	0:1	0.000	1.00
	1:0	1.04	0.00
	1:0	0.956	0.00
	1.6:1	1.435	0.77
	2:1	1.23	0.60



(a)

FIG. 4 Static and constant fatigue-life curves for rupture of glass-polyester thin-walled tubes with two different orientations between the principal material axes and the principal loading directions (a) $\alpha = 0°$ and (b) $\alpha = 45°$ [21].


λ=+1
200
λ=0
λ=+2
CYCLES
10^3
STATIC
100
10^4
10^5
10^6
MAXIMUM AXIAL STRESS (MPa)
MAXIMUM HOOP STRESS, (MPa)
0
100
200
300
λ=∞
-100
λ=-2
-200
λ=-1
λ=0

(b)

FIG. 4 (cont)

were greater in equibiaxial tension (λ = 1) than uniaxial tension by approximately 30% for the same hole radius, Fig. 5.

Biaxial strength data exist for cruciform-shaped specimens containing sharp cracks and slots. Daniel [28] tested quasi-isotropic $[0/\pm45/90]_S$ graphite-epoxy cruciform specimens containing sharp cracks inclined at 30° to the principal loading direction and parallel to a principal material axis. The static failure strengths in biaxial tension were approximately 20% below the uniaxial value indicating an appreciable contribution to failure by the shear stress, Fig. 6. Pascoe and Tutton [17] tested cruciform specimens containing two transverse edge slots oriented at 45° to both the principal material axis and the principal loading axis. These specimens were also fabricated using a quasi-isotropic graphite-epoxy composite. The static failure strength for this type of geometric discontinuity was not significantly affected by the biaxiality of loading. It is difficult to draw any conclusions from the results of Daniel and Pascoe and Tutton other than to suggest that the effects of biaxial loading on static strength depend on the nature of the geometric discontinuity, and its orientation with respect to both the principal material axis and principal loading direction.

5. EFFECTS OF BIAXIAL LOADING ON FATIGUE PROPERTIES

The assessment of multiaxial fatigue behaviour of composites is very important not only for the safe and reliable operation of composite structures and components but also for a more complete understanding of the fundamental nature of the cyclic damage and failure mechanisms. The few papers published on this subject have shown that multiaxial loading can have a considerable effect on the fatigue lives of composite materials [13,21,29-33]. For example, Owen, Found and Griffith [13,21] observed that the fatigue lives of glass-polyester thin-walled tubes, with the principal material axes parallel to the principal loading directions (α = 0), decreased by a factor of approximately 100 when the biaxial stress ratio λ changed from +0.5 to -1.0. This decrease in fatigue life was much greater when the principal material axes where inclined at 45° to the principal loading directions, as shown for example in Figs 4 and 7.

TABLE 4: Effect of biaxial stress ratio on the tensile static strength parallel to the principal material axis of $[0/\pm45/90]_s$ graphite-epoxy cruciform-specimens containing 25 mm diameter holes [26].

Biaxial stress ratio (λ)	Breaking load (kN)	Static failure strength (MPa)
0	55.2	349
0	56.9	356
0.5	64.9	405
1.0	81.0	507

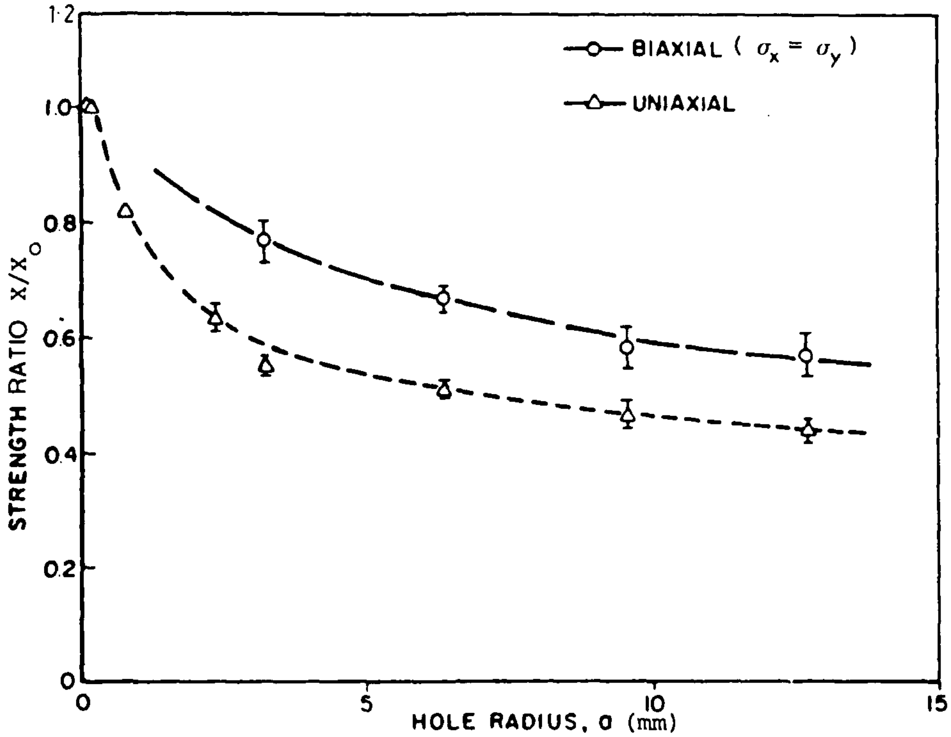


FIG. 5 Strength reduction as a function of hole radius for a $[0/\pm45/90]_s$ graphite-epoxy plate under uniaxial and biaxial tension [X_o is the yield strength for an unnotched uniaxial specimen] [27].

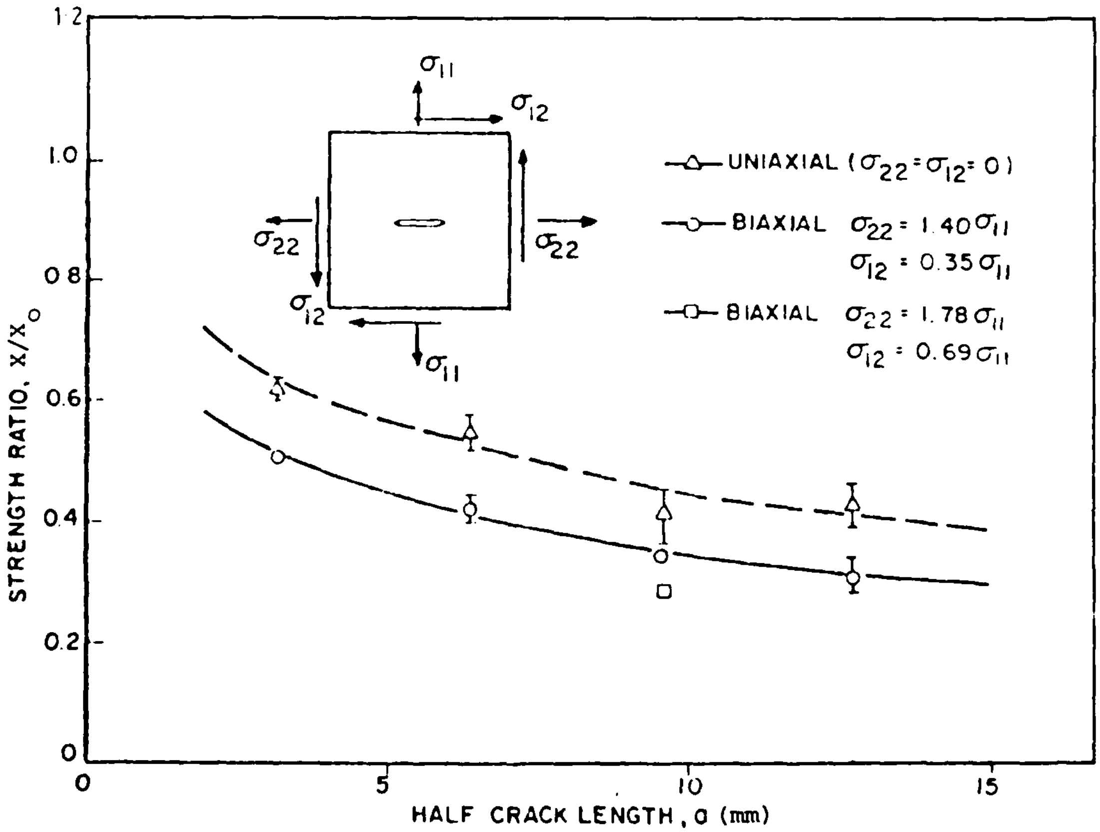


FIG. 6 The effect of biaxial loading including a shear component on the strength of a $[0/\pm45/90]_s$ graphite-epoxy plate containing a crack. The shear component was produced by inclining both the fibre axes and the crack at 30° to the side of the specimen. [X_o is the yield strength of an unnotched uniaxial specimen] [28].

Francis and coworkers [29,30] observed similar changes in the fatigue lives of graphite-epoxy thin-walled tubes containing a small hole and having a [±45] layup, Fig. 8. A power law was fitted to the data using regression analyses i.e.

$$\sigma_{max} = AN^{B} \tag{3}$$

where A and B are the co-efficient and exponent respectively, σ_{max} is the maximum stress of the cycle and N is the number of cycles to failure. The results of this analysis (given in Fig. 8) showed that the coefficient decreased with increasing tension to torsion ratio. Figure 8 also shows that when the tension to torsion ratio is 1:1 the fatigue life is reduced by a factor of about 100 compared with tension alone, and that when the ratio is 1:2 the life reduction is much greater.

In order to compare the results on a more scientific basis the octahedral shear stresses were calculated for each of the conditions. Figure 9 shows the transformed data. On this basis the multiaxial effects are reversed but again large differences in life are apparent.

Wang, Chim and Socie [31] studied the biaxial fatigue behaviour of glass-epoxy (G-10 grade) tubular specimens subjected to in-phase cyclic tension and torsion loading at cryogenic temperatures. They found strong biaxial effects and their conclusions can be summarised as follows:

i) At any given cyclic axial stress range the fatigue life was considerably reduced by increasing the cyclic shear stress range, Fig. 10.

ii) Similarly, at any given shear stress range the fatigue life decreased by increasing the cyclic axial stress range, Fig. 11.

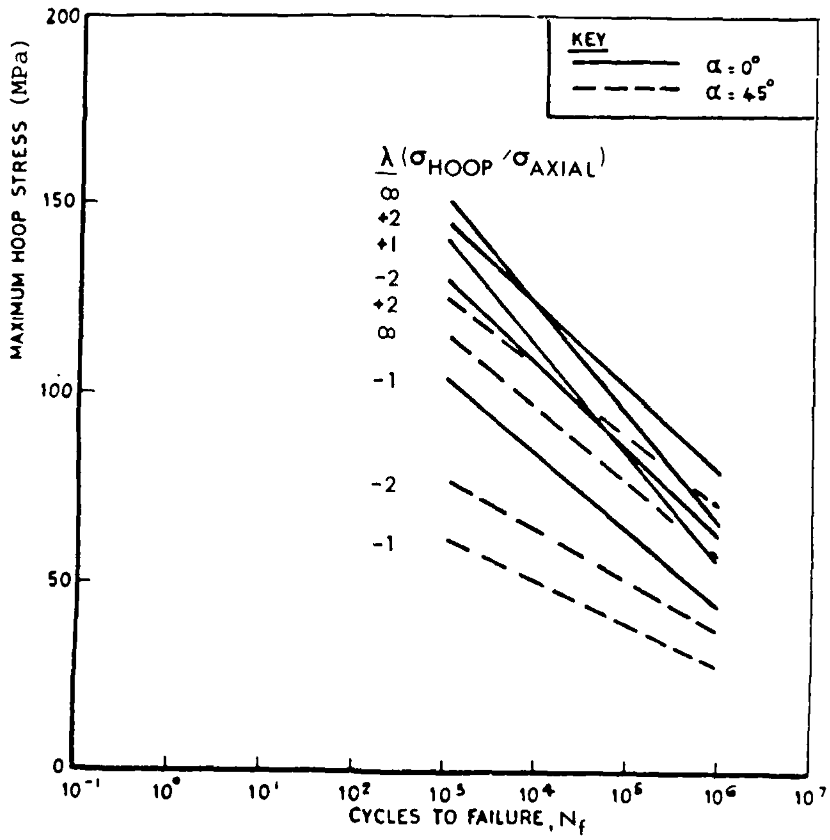


FIG. 7 Stress-life curves for biaxial fatigue loading of a glass-polyester composite for two orientations of the principal material axes to the principal loading axes: $\alpha = 0$ and $\alpha = 45°$ [21].

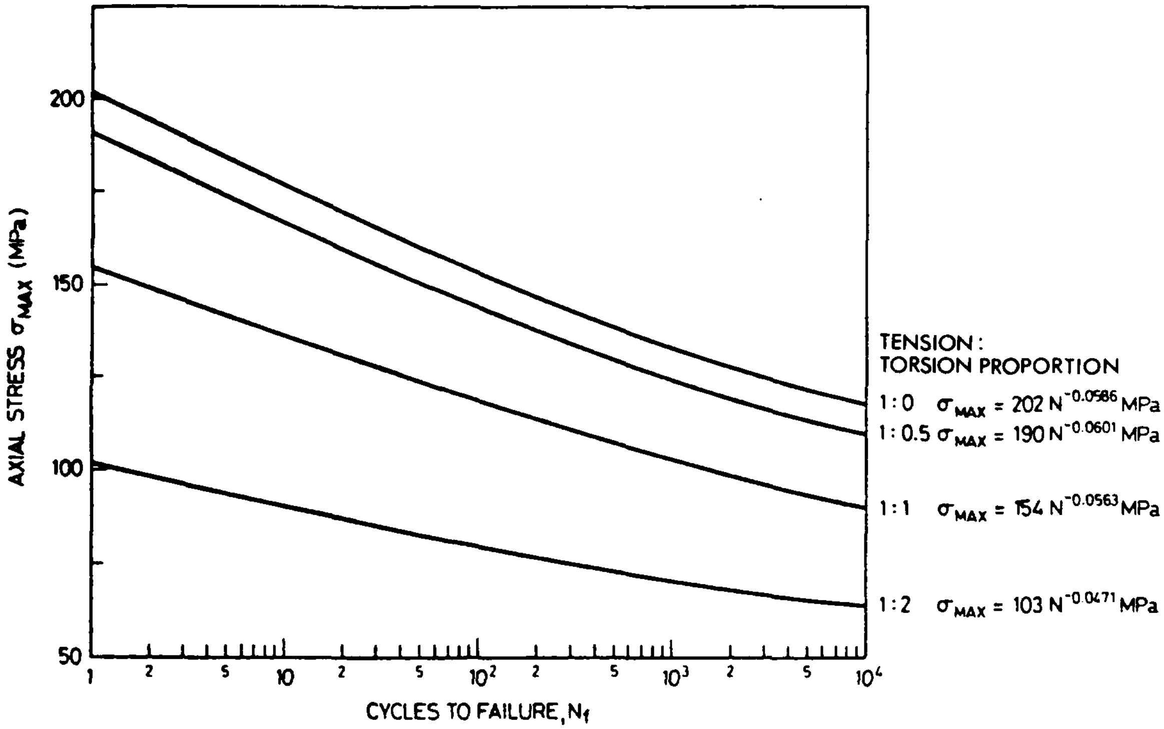


FIG. 8 Maximum axial stress-life curves for biaxial fatigue loading of $[\pm45]_S$ graphite-epoxy tubes with a 4.8 mm diameter hole [29].

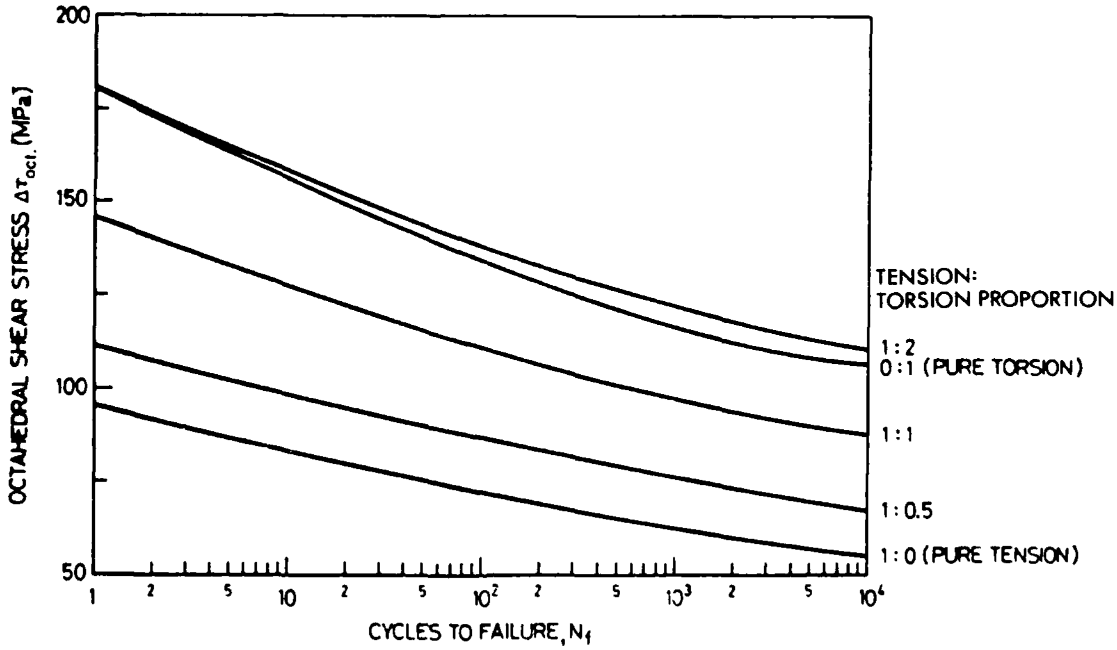


FIG. 9 Octahedral shear stress-life curves for biaxial fatigue loading of $[\pm45]_S$ graphite-epoxy tubes with a 4.8 mm diameter hole [29].

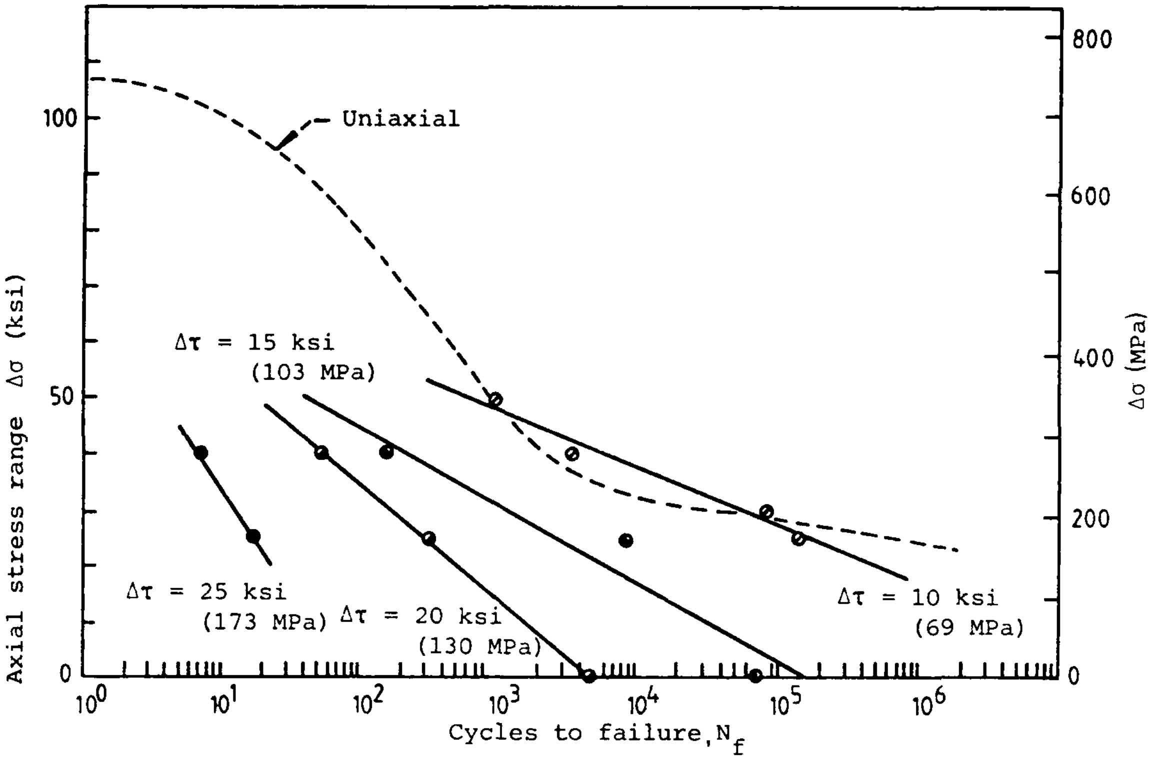


FIG. 10 Axial tensile stress range Δσ versus cycles to failure curves for several values of shear range versus Δτ in cryogenic biaxial fatigue of a glass-epoxy composite [31].

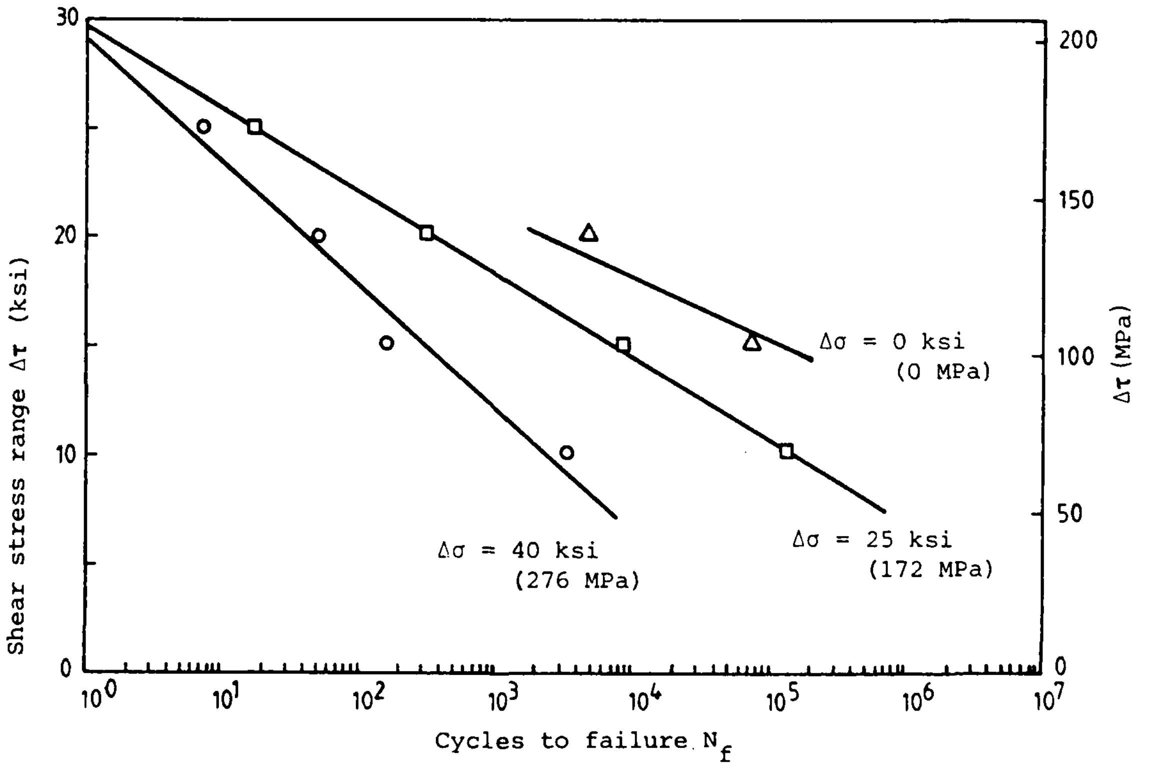


FIG. 11 Shear Stress range Δτ versus cycles to failure curves for several values of axial tensile stress range Δσ in cryogenic biaxial fatigue of a glass-epoxy composite [31]

iii) The damage mechanisms were generally very complex. Extensive matrix cracking, fibre/matrix debonding, tensile fracture of load bearing fibres, microbuckling of fibre bundles and interlayer delamination all occurred during the fatigue loading. The severity of the individual mechanisms was closely related to the magnitudes of the different stress components and the biaxial stress ratio.

With reference to damage mechanisms, Smith and Pascoe [32,33] also observed several types of damage in a woven roving glass-polyester composite under various biaxial fatigue conditions at room temperature. These mechanisms depended on stress state, cyclic frequency and orientation of the principal material axis with respect to the principal loading direction.

Smith and Pascoe [32,33] also examined the effects of biaxial loading on the cyclic stress-strain behaviour of woven roving glass-polyester cruciform-shaped specimens. They found that the hysteresis behaviour was dependent on stress state, as shown for example in Fig. 12. When the stress state was equibiaxial ($\lambda = 1$), a distinct knee occurred in the first tensile half cycle but it disappeared on subsequent tensile half-cycles, whereas a linear stress-strain relationship was observed during the first compressive half cycle, Fig. 12(a). It was suggested that this behaviour indicated irrecoverable damage during the first tensile half cycle, such as breakdown of the fibre/matrix bond and matrix cracking. During subsequent cycles the amount of hysteresis was small and approximately constant, whereas the tensile and compressive modulii began to change with the difference increasing with the number of cycles. In comparison, for shear loading ($\lambda = -1$), the stress-strain curve for the first cycle did not exhibit a distinct knee and there was a marked build up in hysteresis energy with increasing number of cycles, Fig. 12(b). Also the stress-strain behaviour for shear loading was markedly dependent on cyclic frequency whereas for equibiaxial loading the behaviour was not affected by frequency.

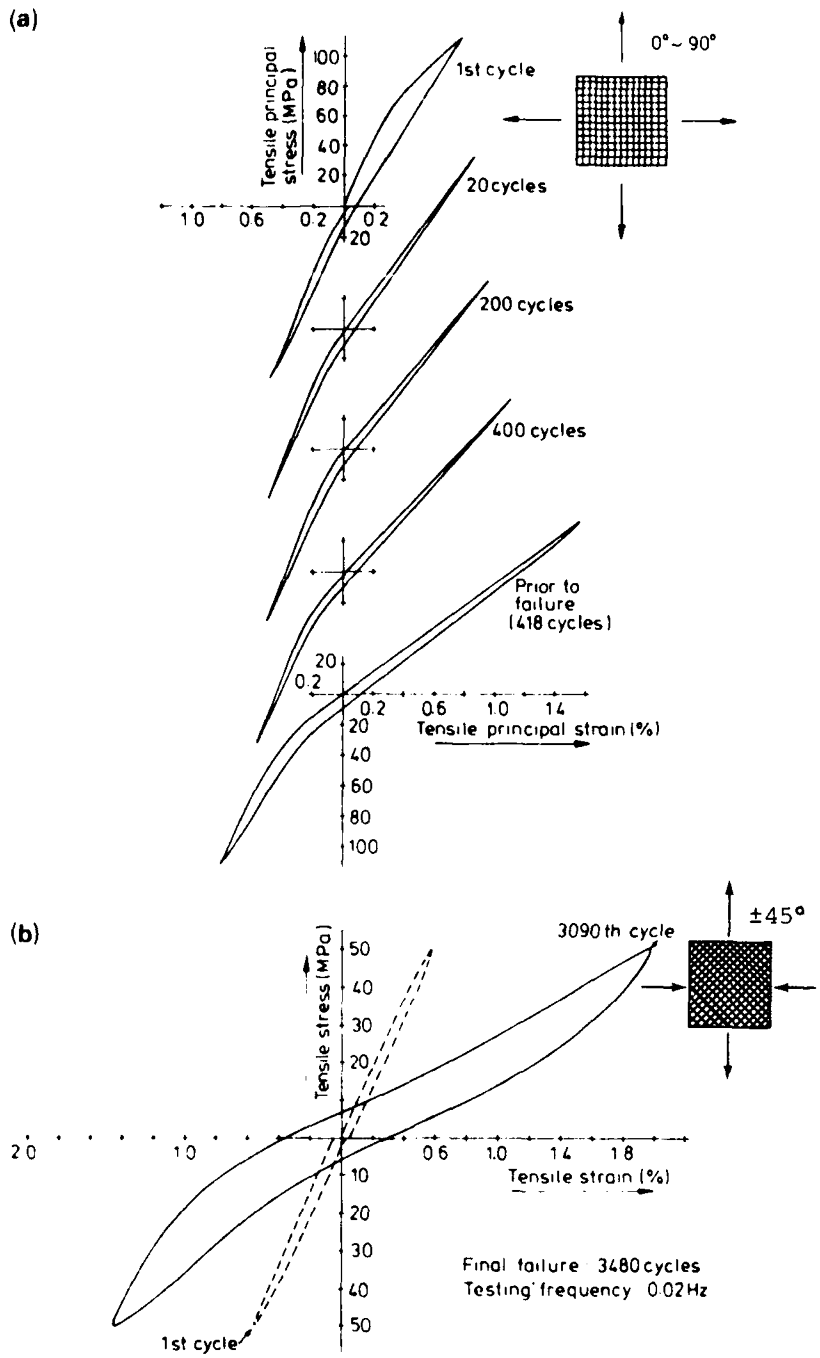


FIG. 12 Progressive stress-strain loops for a woven roving glass-polyester composite subject to biaxial loading (a) equibiaxial stress (λ = +1) and (b) shear stress along the fibres (λ = -1) [33].

The effects of biaxial loading on fatigue crack growth rates in composite materials have been reported by Radon and Wachnicki [34,35]. They tested chopped strand mat glass-polyester centre-notched cruciform specimens. Results from this work showed that biaxial loading did not produce a significant change in the fatigue crack growth rate ($\frac{da}{dN}$) as shown in Fig. 13. However, this result is surprising given the large effect of biaxial stress states on the fatigue life curves of fibre-reinforced composite materials. Therefore, more experimental data, including that for other fibre/matrix and layup combinations, are required to confirm these results.

6. CONCLUSIONS

A review of the limited number of papers in the literature on multiaxial fatigue and fracture of composites has suggested that biaxial stress states may increase static limit strengths by up to approximately 50%, increase ultimate strengths by approximately 30%, decrease fatigue lives by factors of up to several orders of magnitude and change both the cyclic stress-strain behaviour and the failure modes in a complex manner. However, more multiaxial fatigue data covering a greater range of fibre/matrix and layup combinations are required to assess the general validity of these trends. There is also a need for more biaxial fatigue crack propagation data for composites. In addition, none of the presently available multiaxial failure theories for composites agree with the observed experimental results with sufficient accuracy to be confidently used for design purposes.

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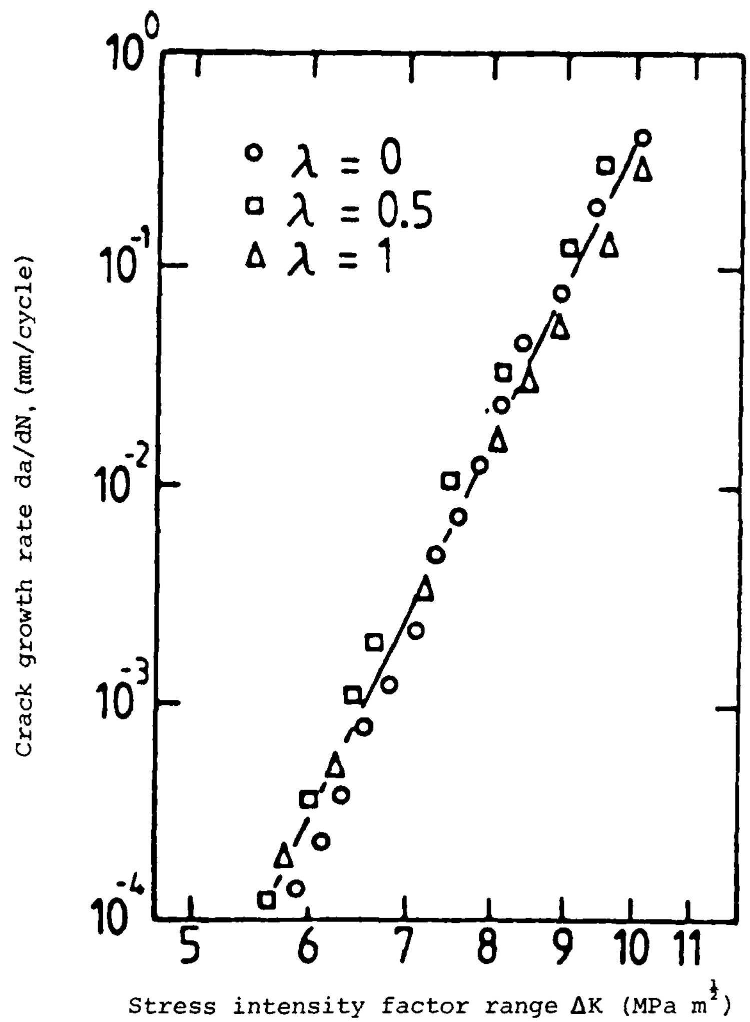

FIG. 13 Relationship between fatigue crack growth rate (da/dN) and stress intensity factor range perpendicular to the crack line (ΔK) for cnopped strand mat glass-polyester centre-notchea specimens [34].

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